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Second Target Station Project: Moderator Reflector Assembly Hydrogen Static Heat Load Analysis

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MODERATOR REFLECTOR HYDROGEN STATIC HEAT LOAD ANALYSIS

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July 2026

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CONTENTS

ABSTRACT

The Moderator Reflector Assembly design attempts to reduce heat transfer to the cryogenic hydrogen flowing to and in the moderators by providing vacuum insulation, low emissivity surfaces, and low conductivity vacuum spacers around the hydrogen boundary. The heat transfer by convection is negligible; however, the conduction and radiative heat transfer are appreciable and will be calculated to be used in the design of the Cryogenic Moderator System.

1. INTRODUCTION

The Moderator Reflector Assembly (MRA) features 2 liquid hydrogen moderators and hydrogen transfer lines to deliver hydrogen from the Cryogenic Moderator System transfer lines to the moderators. The liquid hydrogen in these structures will operate between 18 and 22 K and is vacuum insulated to minimize heat transfer from the surrounding structures to the cold surfaces. Both the cold surfaces and the insides of the vacuum boundaries are polished to minimize radiative heat transfer and low thermal conductivity titanium with thin profiles is used for spacers that keep the cold structures aligned within the vacuum boundaries to minimize heat conduction. While vacuum insulation is effective at reducing convective heat transfer to a negligible value, appreciable heat transfer occurs via radiation and conduction. While this heat transfer is small relative to the neutronic heating in the hydrogen and hydrogen boundary materials, it is still significant and important to the design of the CMS and the MRA.

This document will estimate the static heat transfer to the MRA liquid hydrogen by both radiation and conduction to provide static heat loads for the MRA-CMS Interface Sheet [1] for use in CMS design. These heat loads have significant uncertainty associated with the uncertainty in the emissivity values for the surfaces and the contact resistances for the spacers.

2. GEOMETRY

The MRA hydrogen lines are connected at the top of the core vessel to the CMS hydrogen lines and travel down through several jogs to the upper backbone, as seen in Figure 2.1. The hydrogen transfer lines run parallel to each other in the MRA backbone within a common vacuum chamber, but are isolated into individual vacuum boundaries when passing from the backbone into the vacuum vessels. Each hydrogen vessel is supported by 6 titanium pins with 3 mm diameter and length. The hydrogen lines are supported within the vacuum boundary by titanium vacuum spacers which are spaced to prevent contact between the hydrogen lines and surroundings while not over constraining the hydrogen lines, as seen in Figure 2.2.

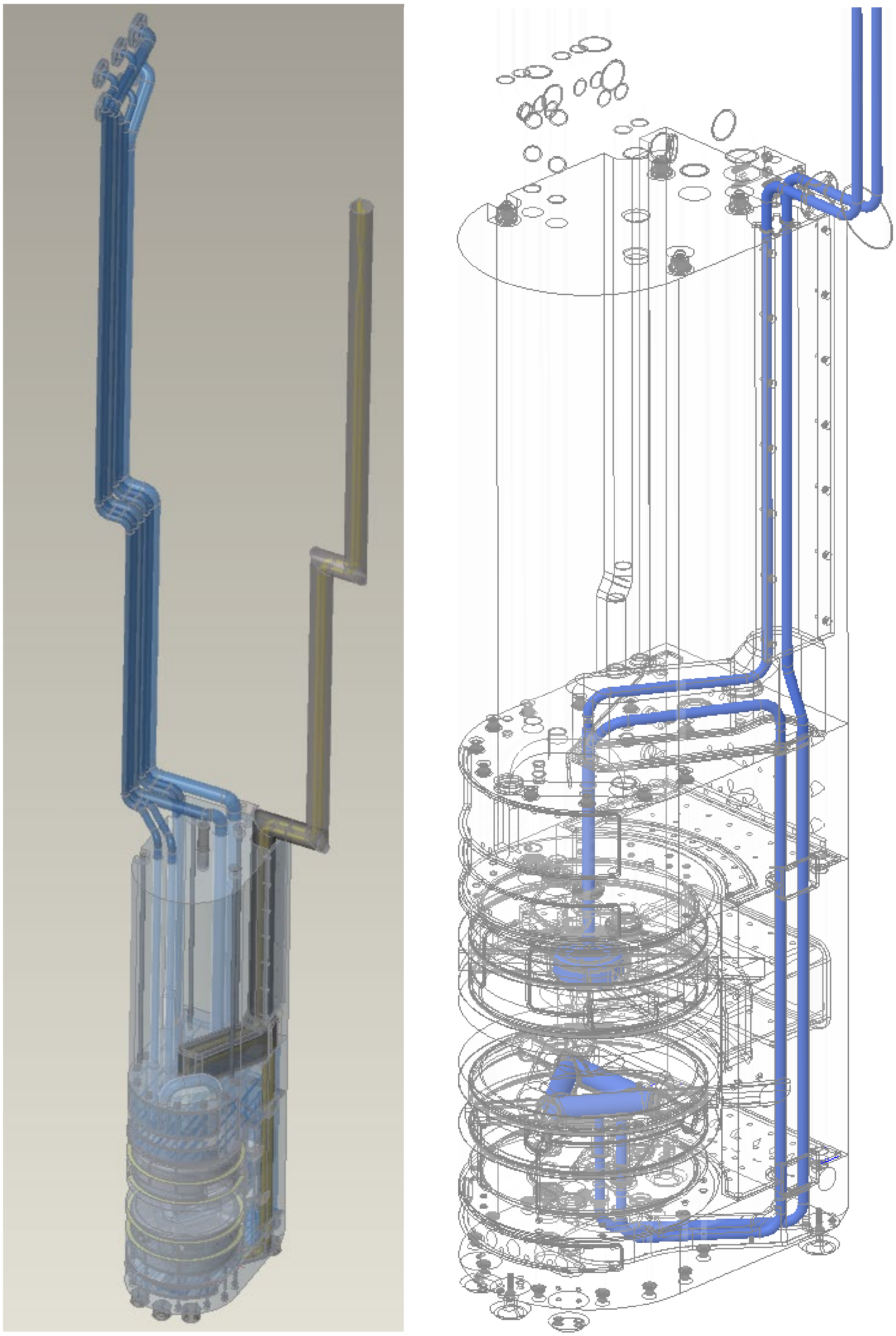

Figure 2.1 Hydrogen Lines (Yellow) within Transparent MRA (left), Hydrogen Boundary with Wireframe MRA (right)

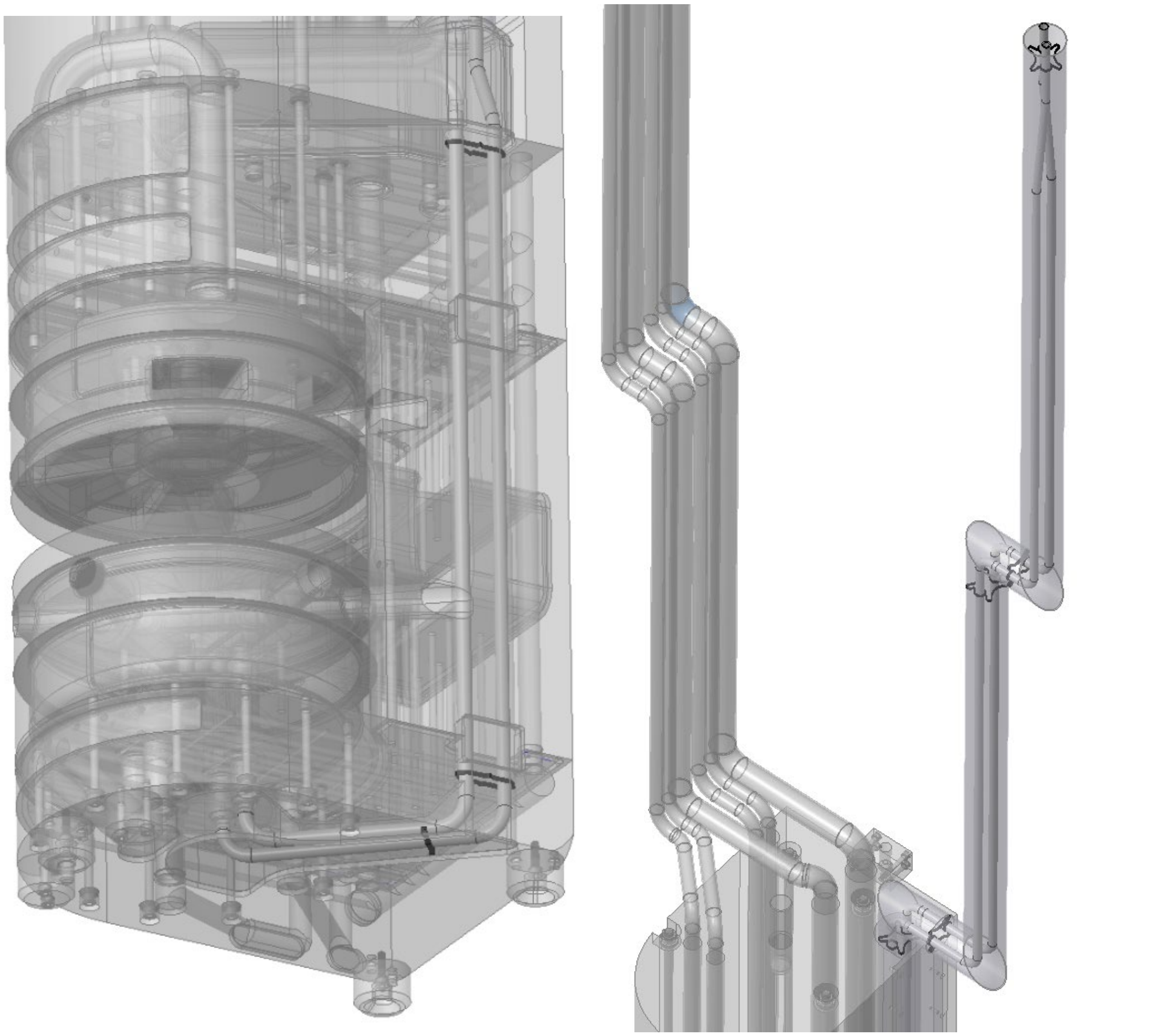

Figure 2.2 MRA Hydrogen Line Spacers (Black) within the Backbone (left), MRA Hydrogen Transfer Line Spacers (Black) (right)

3. MATERIAL PROPERTIES

3.1 EMISSIVITY VALUES

Emissivity values depend on material, surface condition, and surface temperature and generally range quite significantly. Values for most materials were assumed to 0.2, which is near the maximum value for polished metals, as seen in Table 3.1. Only the cryogenic aluminum surface of the hydrogen vessels and electropolished surfaces of the transfer line vacuum tubing were assumed to have an emissivity of 0.1.

Table 3.1 Component Materials and Emissivities

Component	Material	Surface Condition	Temperature Range (K)	Emissivity
Hydrogen Vessel	6061-T6 Aluminum	Polished	18-25	0.1
Vacuum Vessel	6061-T6 Aluminum	Polished	305-315	0.2
Hydrogen Vessel Extensions	Invar	Polished	18-22	0.2
Vacuum Vessel Extensions	316L Stainless Steel	Polished	305-349	0.2
Hydrogen Tubing	Invar	Polished	18-22	0.2
Backbone	316L Stainless Steel	Polished	305-358	0.2
Vacuum Tubing	316L Stainless Steel	Electropolished	305-338	0.1

3.2 THERMAL CONDUCTIVITY

The titanium pins and spacers which separate the cold hydrogen surfaces from the warm vacuum surfaces are specified to be made from Ti 15-3-3-3, which has one of the lowest thermal conductivities of any metal. Using National Institute of Standards and Technology correlation [2], thermal conductivity and corresponding thermal conductivity integral from 18 K were plotted in Figure 3.1. Note that the thermal conductivity integral was calculated from 18 K to the temperature on the X-axis of the plot.

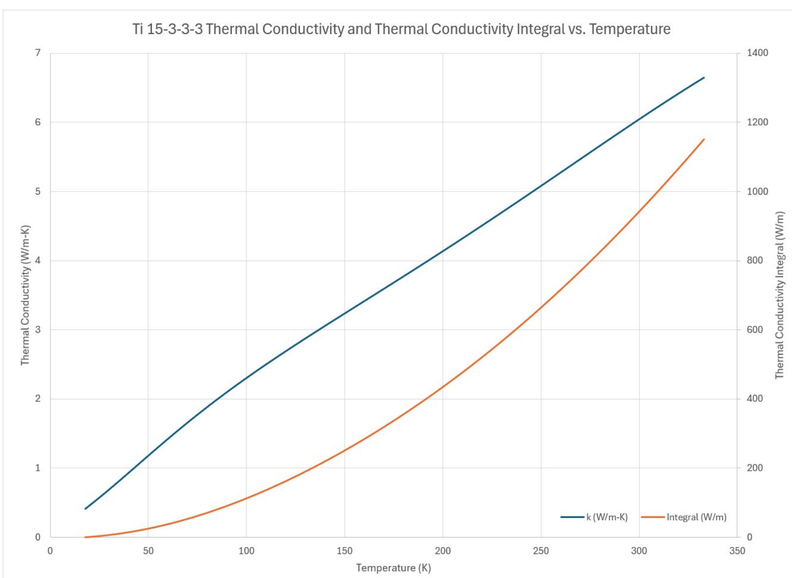

Figure 3.1 Ti 15-3-3-3 Thermal Conductivity and Thermal Conductivity Integral Vs. Temperature

4. RADIATION HEAT TRANSFER

4.1 VIEW FACTORS AND SURFACE AREAS

In the reflector vessels and the connections from the backbone to the reflector vessels, the hydrogen boundary is a single convex surface within an enclosure, so the view factor is simply 1. In the backbone and transfer line sections, two hydrogen tubes run parallel to each other. Using the assumption of infinitely long tubes, the view factor from one hydrogen tube to the other is calculated to be 0.06 [3]. Since the tubes are convex, the view factor from the hydrogen tube to itself is 0. Using the summation rule, the view factor from the hydrogen tube to the vacuum tube is then 0.94. It should be noted that with polished, low emissivity surfaces, the radiation heat transfer is not very sensitive to the view factor.

The surface area for the hydrogen tubes was estimated by calculating the tube length of each section and multiplying by the tube circumference. The surface areas of the more complex geometry was extracted from the CAD models as shown in Figure 4.1, Figure 4.2, and Figure 4.3.

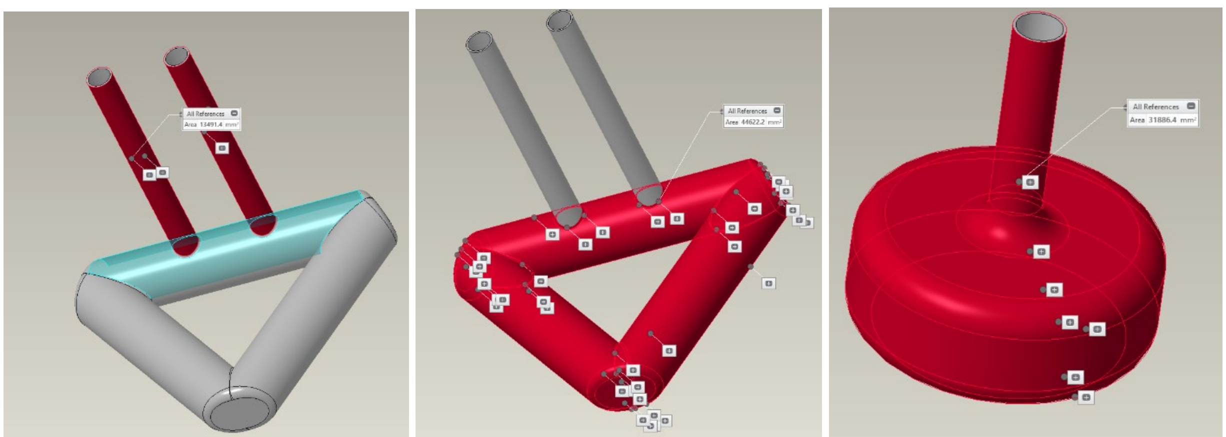

Figure 4.1 Hydrogen Vessel Surface Area Measurements

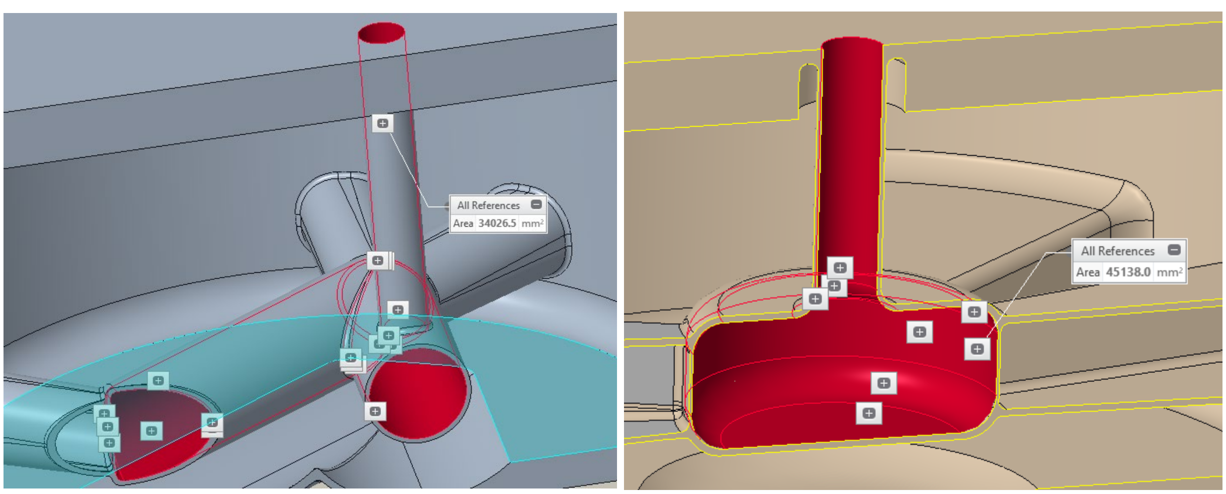

Figure 4.2 Vacuum Vessel Enclosure Surface Area Measurements

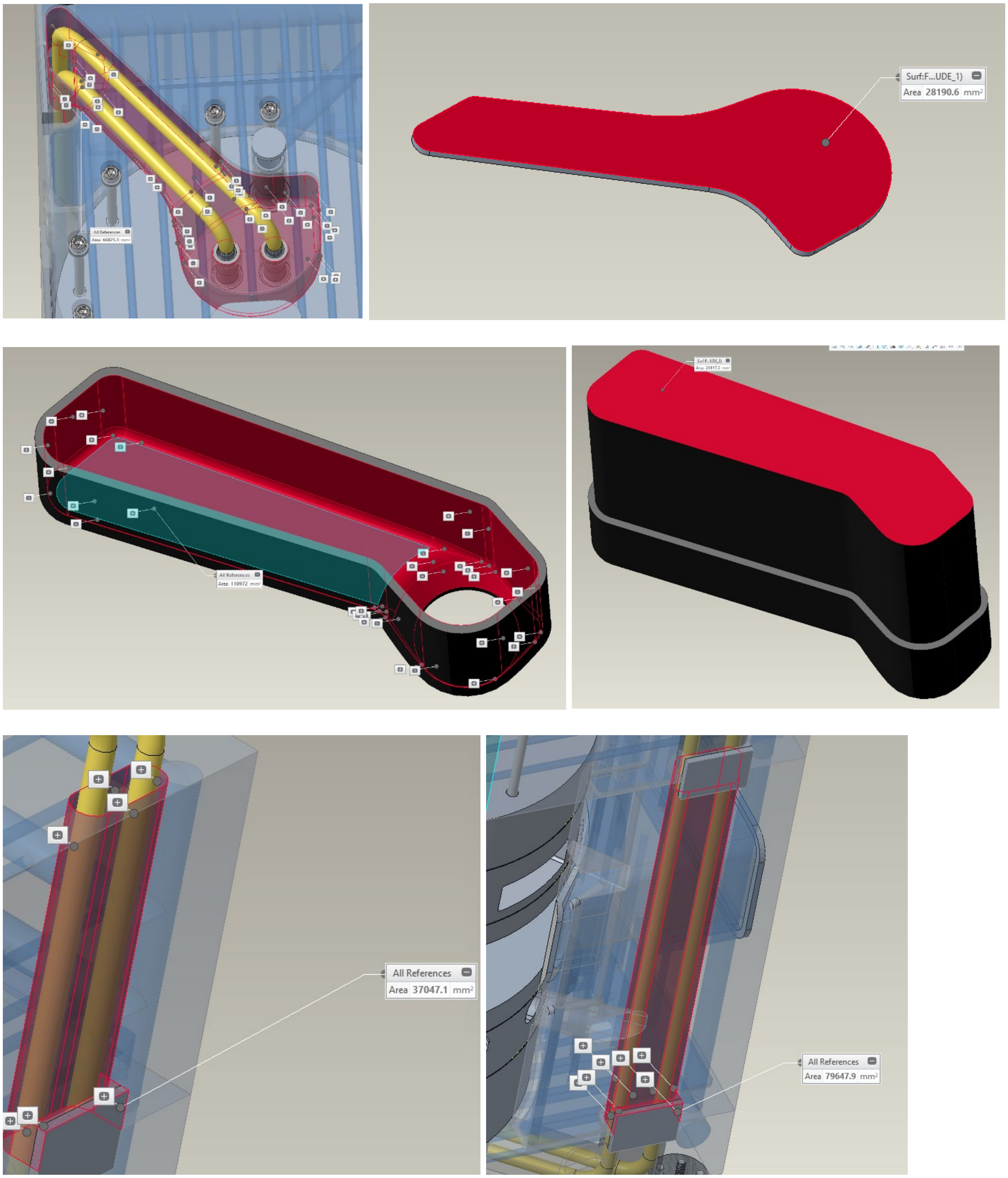

Figure 4.3 Backbone Vacuum Enclosure Surface Area Measurements

4.2 ENCLOSURE RADIATION CALCULATIONS

Radiation heat transfer is calculated using formula 13.18 from [4] for two gray surfaces that form an enclosure.

$$q = \frac{\sigma\left(T_1{}^4 - T_2{}^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

The hydrogen boundary surface is always assumed to be at 18.34 K, although the boundary surface temperatures range from 18.34-25 K when the beam is on. This assumption has negligible impact on the heat transfer calculated. We will calculate the static heat load with both beam on and beam off conditions. For beam on conditions, the highest temperature value in the vacuum boundary from the MRA Thermal Hydraulic Analysis [5] was used so the values are conservative. The results of the calculation, shown in Table 4.1, are total radiation heat transfer of 58 W beam on and 39 W beam off for the MRA hydrogen boundary, with about half of the heat transfer occurring in the transfer line.

Table 4.1 Radiation Heat Transfer for the MRA Hydrogen Boundary

Component	Hydrogen Boundary			Vacuum Boundary			View Factor H to V	Beam On		Beam Off	
	Material	Area (mm^2)	Emissivity	Material	Area (mm^2)	Emissivity		V Temp (°C)	q (W)	V Temp (C)	q (W)
Upper H Vessel	Al 6061-T6	31886	0.1	Al 6061-T6	45138	0.2	1	40.6	1.36	32.2	1.22
Upper H Extend 1	Invar	10806	0.2	Al 6061-T6	13208	0.2	1	73.1	1.06	32.2	0.64
Upper H Extend 2	Invar	2791	0.2	316	3411	0.2	1	73.1	0.27	32.2	0.17
								Upper Reflector Total	2.70		2.03
Lower H Vessel	Al 6061-T6	58114	0.1	Al 6061-T6	68053	0.2	1	40.6	2.38	32.2	2.13
Lower H Extend 1	Invar	1885	0.2	Al 6061-T6	2388	0.2	1	40.6	0.13	32.2	0.11
Lower H Extend 2	Invar	2827	0.2	316	3581	0.2	1	40.6	0.19	32.2	0.17
								Lower Reflector Total	2.69		2.42
Upper Backbone	Invar	65501	0.2	316	171837	0.2	0.94	63.6	7.24	32.2	4.89
Middle Backbone	Invar	48107	0.2	316	79648	0.2	0.94	76.1	5.42	32.2	3.16
Lower Backbone	Invar	35065	0.2	316	95016	0.2	0.94	84.6	4.97	32.2	2.64
MRA Transfer Line	Invar	360101	0.2	316	826793	0.1	0.94	65.2	29.73	32.2	19.72
								Total	58.14		39.30

5. CONDUCTION HEAT TRANSFER

5.1 HYDROGEN VESSEL PINS

Each hydrogen vessel is supported by 6 titanium 3 mm diameter pins which are 3 mm long, as shown in Figure 5.1. The pins provide alignment for the hydrogen vessel while minimizing heat transfer from the vacuum boundary. We will conservatively assume no contact resistance at either end of the pin, so that one end is at 18K while the other is at the temperature of the vacuum vessel. Since the cross sectional area of the pin is constant, the conduction calculation is straightforward using the thermal conductivity integral [6].

With beam on, the vacuum vessels operate at about 40°C.

$$q = \Theta * \frac{A}{L} = 1021 \frac{W}{m} * \frac{7.07mm^2}{3mm} = 2.41W$$

With beam off, the vacuum vessels operate at 32°C.

$$q = \Theta * \frac{A}{L} = 972 \frac{W}{m} * \frac{7.07mm^2}{3mm} = 2.29W$$

Because there are 6 pins for each hydrogen vessel, the total estimated conduction heat transfer is 14.4 W with beam on and 13.7 W with beam off for each hydrogen vessel.

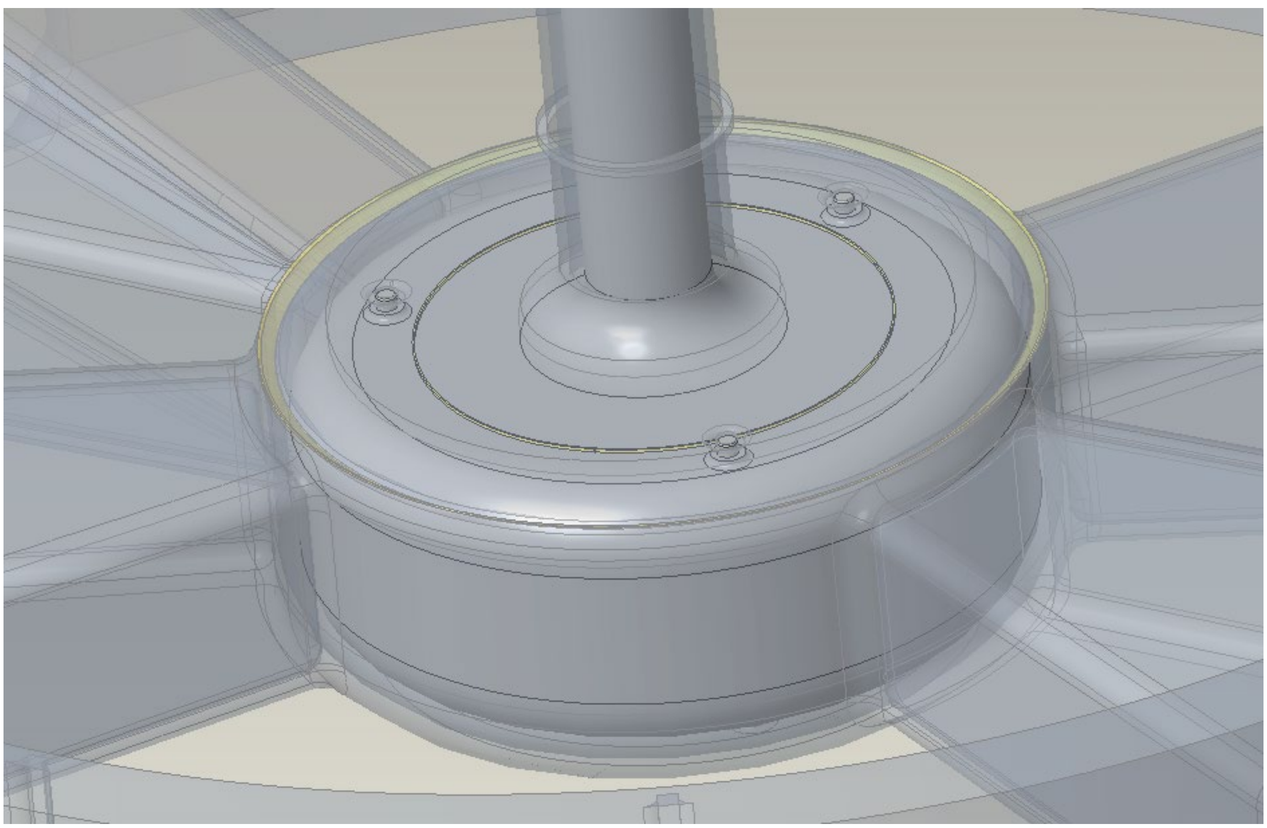

Figure 5.1 Each Hydrogen Vessel is Supported by 6 Pins, 3 Each Top and Bottom

5.2 MRA BACKBONE SPACERS

The use of spacers within the backbone is minimized to avoid over constraint of the piping. As a result, 2 spacers are used in the vertical chase through the entire backbone and 1 spacer is used in the lower backbone We will conservatively assume no contact resistance at either end of the spacer, so that one end is at 18K while the other is at the temperature of the transfer line, which is assumed to be 60°C with beam on and 32°C with beam off. Since the cross sectional area of the spacer legs is constant, with 6 mm spacer length and 1 mm leg thickness, the conduction calculation is straightforward using the thermal conductivity integral [6]. Note that each spacer has 4 legs from the hydrogen boundary to the vacuum boundary as seen in Figure 5.2.

With beam on:

$$q = \Theta * \frac{A}{L} = 1150\frac{W}{m} * \frac{4 * 6mm^2}{10mm} = 2.76W$$

With beam off

$$q = \Theta * \frac{A}{L} = 972\frac{W}{m} * \frac{4 * 6mm^2}{10mm} = 2.33W$$

The total conduction heat transfer for the MRA backbone spacers is 8.28 W with beam on and 6.99 W with beam off.

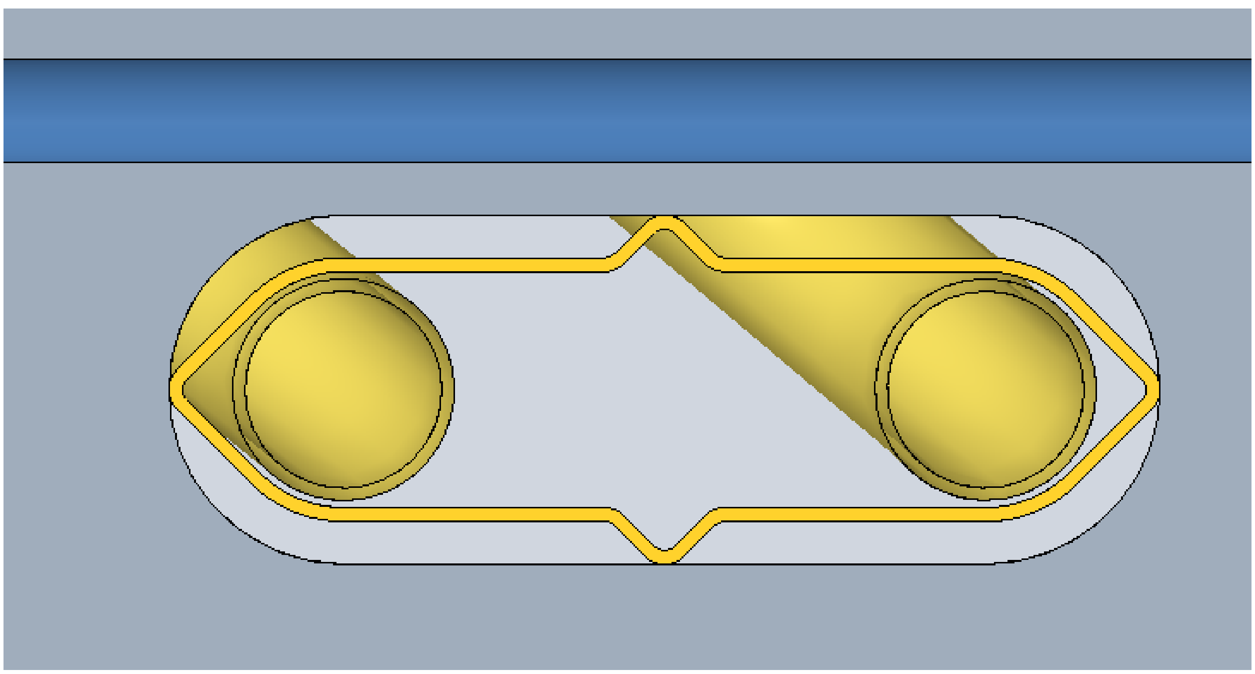

Figure 5.2 MRA Backbone Spacer Arrangement

5.3 MRA TRANSFER LINE SPACERS

As shown in section 2, there are 5 titanium spacers located in the MRA transfer line to align the hydrogen tubes within the vacuum tubes. We will conservatively assume no contact resistance at either end of the spacer, so that one end is at 18K while the other is at the temperature of the transfer line, which is assumed to be 32°C with both beam on and beam off. Since the cross sectional area of the spacer legs is constant, with 6 mm spacer length and 1 mm leg thickness, the conduction calculation is straightforward using the thermal conductivity integral [6]. Note that each spacer has 4 legs from the hydrogen boundary to the vacuum boundary as seen in Figure 5.2.

$$q = \Theta * \frac{A}{L} = 6.38\frac{W}{m} * \frac{4 * 6mm^2}{20mm} = 1.17W$$

The total conduction heat transfer for the MRA transfer line spacers is 5.83 W.

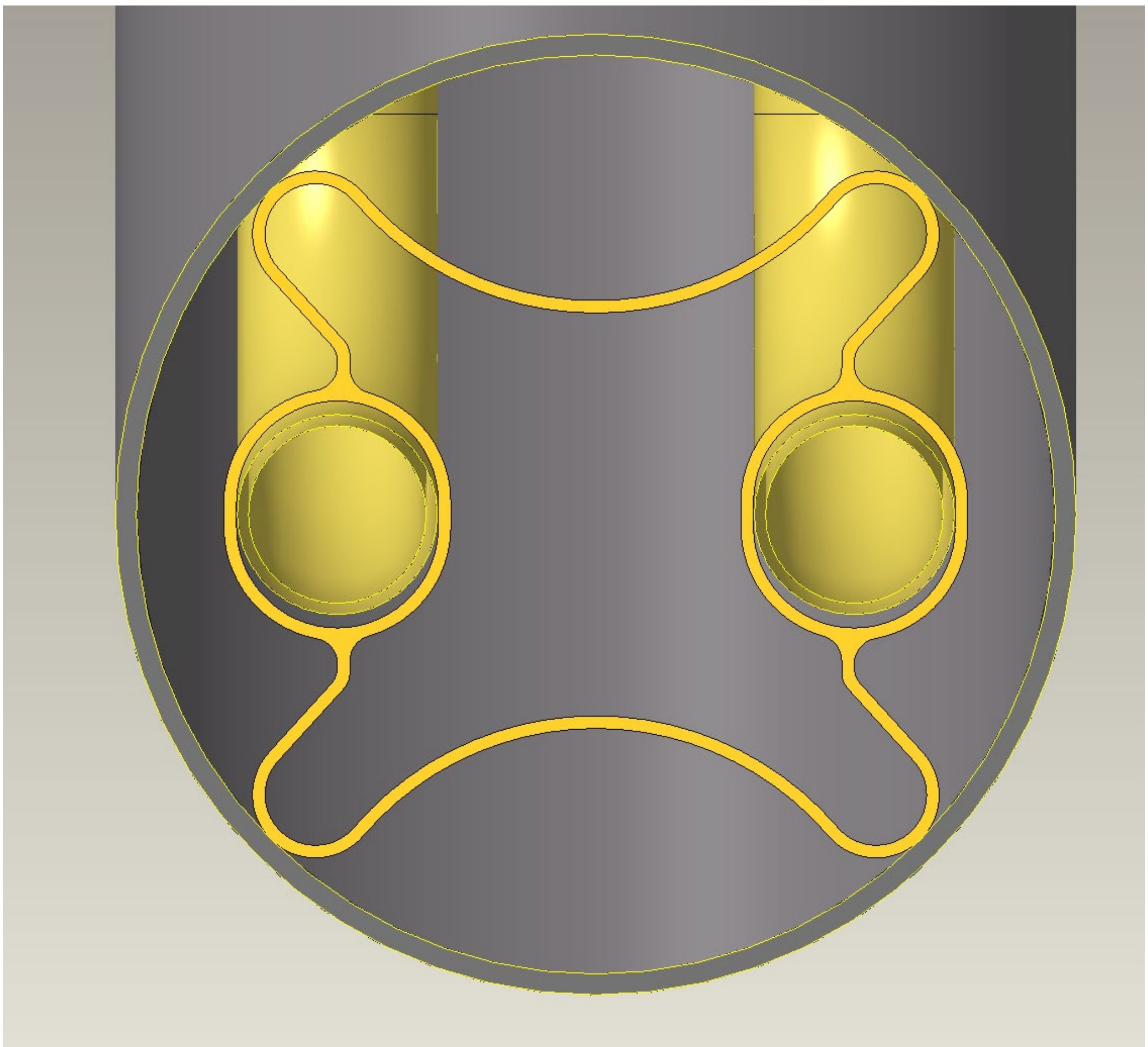

Figure 5.3 MRA Transfer Line Spacer Arrangement

6. CONCLUSIONS

The Moderator Reflector Assembly features hydrogen boundaries which operate at 18 K within a vacuum insulating boundary. The heat transfer by radiation and conduction from the vacuum boundary to the hydrogen has been calculated for all components of the MRA, as shown in Table 6.1. The total static heat load to the MRA hydrogen boundary is estimated to be 96 W with the beam on and 77 W with the beam off.

Table 6.1 MRA Static Heat Load to Hydrogen Boundary Summary

Component	Beam On			Beam Off		
	Q_{rad} (W)	Q_{cond} (W)	Q (W)	Q_{rad} (W)	Q_{cond} (W)	Q (W)
Upper Reflector	2.70	14.4371427	17.14	2.03	14.437143	16.47
Lower Reflector	2.69	14.4371427	17.13	2.42	14.437143	16.85
Upper Backbone	7.24	2.76080582	10.00	4.89	2.3318835	7.22
Middle Backbone	5.42	0	5.42	3.16	0	3.16
Lower Backbone	4.97	5.52161165	10.49	2.64	4.663767	7.30
MRA Transfer Line	29.73	5.82970875	35.56	19.72	5.8297087	25.55
Total	52.75	42.99	95.74	34.86	41.70	76.56

7. REFERENCES

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[2] National Institute of Standards and Technology, "Material Properties: Titanium 15-3-3-3," [Online]. Available: https://trc.nist.gov/cryogenics/materials/Titanium/Titanium.htm.

[3] Incropera, Fundamentals of Heat and Mass Transfer, 2011.

[4] Incropera, Dewitt, Bergman and Lavine, Introduction to Heat Transfer, 2007.

[5] S03040000-DAC10011, "Thermohydraulic Analysis for the Moderator Reflector Assembly (MRA)".

[6] Lakeshore Cryogenics, "Appendix I: Cryogenic Reference Tables".